A hFSM based cognitive control architecture for assistive task in R-MIS

Narcís Sayols[1], Alessio Sozzi[2], Nicola Piccinelli[3], Albert Hernansanz[1], Alicia Casals[1], Marcello Bonfè[2] and Riccardo Muradore[3]

[1]*Universitat Politècnica de Catalunya, Barcelona, Spain*

[2]*Department of Engineering, University of Ferrara, Italy*

[3]*Department of Computer Science, University of Verona, Italy*
narcis.sayols@upc.edu

INTRODUCTION

Nowadays, one of the most appealing and debated challenge in robotic surgery is the introduction of certain levels of autonomy in robot behaviour [1] implying technical advances in scene understanding and situation awareness, decision making, collision-free motion planning and environment interaction. The growth of R&D projects for autonomous surgical robotics (e.g. EU funded I-SUR, MURAB and SARAS) demonstrates the confidence and the expectations of the medical community on the benefits of such technologies. SARAS aims to develop assistive surgical robots for laparoscopic MIS, autonomously operating in the same workspace of either a teleoperated surgical robot or a manually driven surgical tool. The auxiliary robots autonomously decide which task perform to assist the main surgeon, planning motions for executing the task considering the dynamics of human driven tools and patient's organs (predictable only within a short time horizon). This paper proposes a control architecture for surgical robotic assistive tasks in MIS using a hierarchical multi-level Finite State Machine (hFSM) as the cognitive control and a two-layered motion planner for the execution of the task. The hFSM models the operation starting from atomic actions to progressively build up more complex levels. The two-layer architecture of the motion planner merges the benefits of an offline geometric path construction method with those of online trajectory reconfiguration and reactive adaptation. At a global level, the path is built according to the initial knowledge of the operating scene and the requirements of the surgical tasks. Then, the path is reconfigured with respect to the dynamic environment using artificial potential fields [2]. Finally, a local level computes the robot trajectory, preserving collision-free property even in presence of obstacles with small diameter (i.e. the manually driver surgical instruments), by enforcing a velocity modulation technique derived from the Dynamical Systems (DS) based approach of [3].

MATERIALS AND METHODS

The surgical tasks of the auxiliary robots in the surgical environment are modelled as a three-level hFSM:

- Surgeme level: this level are sequences of simple movements that can be performed by the robot (the *surgemes*) to form actions.

- Action level: this level is made of a sequence of actions (a simple tool task with a defined objective) to perform operation phases.

- Phase level: a real surgical procedure is decomposed into a sequence of phases (a complex of surgical actions with a defined intention or objective with a clear beginning and end).

A scheme of the three levels of the hFSM for the Bladder Mobilization task is shown in figure 1.

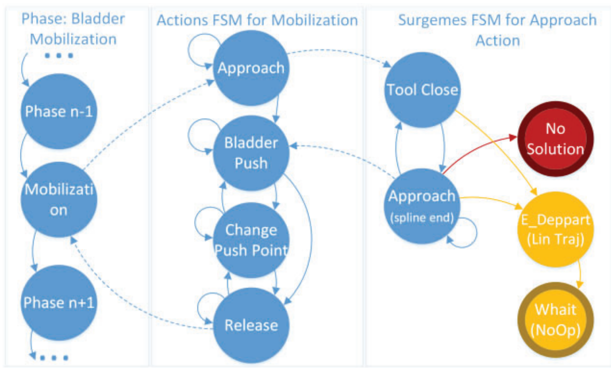

Figure. 1 Scheme of the hierarchical FSM

The transitions between the phases and the actions can be triggered using algorithms of scene understanding, action recognition and action prediction or by direct commands of the main surgeon. The transitions between the surgemes are triggered by the inner controls of the robot or by the motion planner as soon as the relative task is accomplished. Once the surgeme to be executed is determined by the cognitive control, the motion planner generates the trajectory (if the surgeme requires a movement) to accomplish the task. The first layer of the motion planning module, called Dynamic trajectory reconfigurator (DTR), generates a trajectory defined by a set of free of collision control points (CPs) using the current and goal points as well as collision risk information computed as in [4] and the constraints on the motion such as direction to follow at the end or the beginning of the motion. The DTR computes an initial smooth trajectory (C1 third order polynomial) from the current pose to the goal pose (which can be dynamically updated by the hFSM during the trajectory) with the constraints given by the hFSM. This layer returns a set of equally spaced CPs that represent the trajectory. At each control step, the DTR reconfigures the CPs to ensure that the trajectory is collision free in the dynamic environment. These CPs are adapted using artificial potential fields. Each CP is represented as a mass affected by the attraction force to its original position, a repulsion force generated by the other elements in the workspace and a force in the direction of the neighbouring CPs to maintain the coherence in the movement. Moreover, a Depth Map 2D matrix (DM) is computed at each CP to ensure that the whole tool (not only the tip) follow a collision free trajectory. The elements (i,j) of the DM matrix represent the maximum depth reachable for the tool in the direction θi, ϕj (spherical coordinates). The CP is transformed into spherical coordinates with origin in the insertion point of the tool (RCM) to be compared with the values in the DM; if the depth value of the CP is higher than the corresponding element of the DM, the trajectory passing trough that CP would lead a part of the tool to collide with an obstacle, so the CP receives an attraction force towards the RCM in order to be moved to a new position. Finally, the DTR uses the collision free CPs to generate a Catmull-Rom spline that represents the trajectory. The coefficients of this spline are sent to the second layer. The DTR ensures that the CPs are collision free but does not guarantee that the trajectory between two consecutive CPs is collision free too: in fact, the surgical scenario includes cylindrical tools with very thin diameter which can be smaller than the distance between two adjacent CPs. Thus, the second layer, called local modulation planner, is the responsible to compute free collision trajectories between each consecutive pair of CPs exploiting an approach based on the algorithm described in [5]. This algorithm modulates the desired velocity of the robot to obtain a new velocity which drives the robot on a collision free trajectory. The modulation is performed by means of a matrix computed analytically from the geometric features of the obstacles. Since the modulation changes the original trajectory of the robot given by the CPs, a recomputiation of the spline is necessary at the end of the modulation to obtain the new trajectory until the next CP. This new spline will be used in the next control step t+1 to compute the desired velocity.

RESULTS

The method has been validated by performing a realistic surgical task both in a simulated environment and on a real setup. The phase chosen for the validation is the bladder mobilization of the Robotic Assisted Radical Prostatectomy. Figure 1 shows the decomposition of this phase in actions and surgemes. In this phase, the SARAS tools must push down the bladder to make space for the main surgeon avoiding any type of collision with the main tools and the environment. This phase has been chosen because it contains almost all type of surgemes and the trajectory planning has to perform different types of constraint in the movement. This phase is composed of four consecutive actions. In the first action (Approach), the tool is placed over a determined point of the bladder surface. Then the tool pushes the bladder down (Bladder push), creating free space for the surgeon. The pushing position and depth can be changed if required with the Change push point action. Finally (Release), the tool releases the bladder and exits to a safe pose. An emergency action is included to place the tool in a safety pose and exit the action. A snapshot of the approach trajectory (Spline end surgeme for a spline trajectory with constraint on the direction at the end of the motion) of the Approach action is shown in Figure 2.

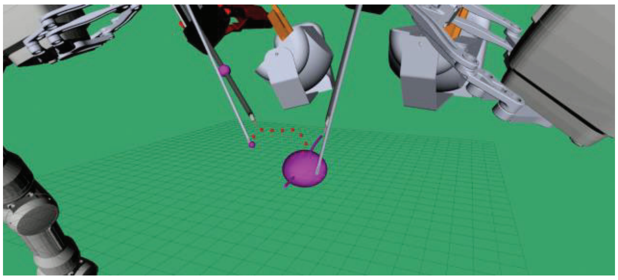

Figure. 2 Example of the trajectory computed and dynamically updated for approaching a virtual bladder

CONCLUSION AND DISCUSSION

We proposed a cognitive control architecture for autonomous execution of assistive task in R-MIS. This architecture is based on a three-level hFSM that models the surgical operation and on a two-layer motion planner which ensures the correct execution of the motions. The proposed architecture has been successfully validated on a realistic surgical task both in a simulated environment and on a real setup.

REFERENCES

[1] Fanny Ficuciello, Guglielmo Tamburrini, Alberto Arezzo, Luigi Villani, Bruno Siciliano, “Autonomy in surgical robots and its meaningful human control”, Paladyn, Journal of Behavioral Robotics, 2019, De Gruyter, vol.10, 1, 30-43

[2] R. R. Murphy, "Potential Fields Methology", Introduction to AI robotics (1st Ed.), MIT Press, 2000, 105-153.

[3] Khansari-Zadeh, S. M. and Billard, Aude, “A Dynamical System Approach to Realtime Obstacle Avoidance”, Autonomous Robots, Springer Verlag, 2012, vol.32, 4,433-454.

[4] A. Hernansanz and A. Casals and J. Amat, "A multi-robot cooperation strategy for dexterous task oriented teleoperation", Robotics and Autonomous Systems, 2015, vol. 68, 156-172.

[5] Sozzi, A., Bonfè, M., Farsoni, S., De Rossi, G. and Muradore, R, “Dynamic Motion Planning for Autonomous Assistive Surgical Robots”, Electronics, MDPI, 2019, vol. 8, 957.